O. Application of Titanium Alloys for Heavy-Duty Vehicles

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Objectives

- Complete the final details of the finite element analysis (FEA) modeling of a diesel engine head and block where an aluminum (Al) casting alloy is used to replace gray cast iron.
- Complete the final details of the FEA modeling of a diesel engine head and block where a magnesium (Mg) casting alloy is used to replace gray cast iron.
- Try to seek funding from either a major diesel engine manufacturer or a major customer to construct and test engines with heads and blocks made from titanium (Ti), Al, or Mg alloys.
- Generate fatigue data that could indicate whether the sub-liquidus casting (SLC) process is attractive for making Al turbocharger compressor wheels with improved fatigue life.

Approach

- Use FEA modeling of a heavy-duty diesel engine head and block to determine whether it is feasible to substitute parts from Ti, Al, and Mg instead of gray cast iron.

Accomplishments

- Confirmed through FEA modeling that it is feasible to substitute Al and Mg for cast iron in the head and block of a heavy-duty diesel engine.
- Conducted a preliminary evaluation of the SLC process. Mechanical property data from A354-T6 samples were generated and compared with data of the same alloy that was permanent mold cast. The data showed that ultimate tensile strength, yield strength, and extrapolated fatigue life for the SLC cast bars was significantly higher than for the permanent mold cast bars.

Future Direction

- Make a more definitive evaluation of the SLC sample after THT Presses delivers higher-quality cast bars.

Project Description and Activities

Modeling Lightweight Alloys

In FY 2004, modeling provided by Ricardo, Inc., using FEA of temperatures and stresses showed that it was feasible to make a heavy-duty diesel engine head and block of cast Ti-6Al 4V instead of gray cast iron. The engine that was modeled was a Cummins 5.9-L B-Series engine (Figure 1). The analysis showed that the only problem was unacceptable temperatures generated in the head valve bridges; therefore, a novel means of mitigating this effect was proposed and modeled. The novel approach was to substitute for the Ti in the valve bridges a high-thermal-conductivity alloy insert of Be-Cu. The engine was again modeled, but the normal 305-hp rating used for modeling was increased by 50% to 450 hp. The model showed that this approach was viable and resulted in a 10% weight savings as well as a higher horse power. It was felt that these advantages could be attractive to the military, specifically TACOM. In FY 2005, numerous presentations were made to the diesel engine companies, to Oshkosh Truck, and to the Defense Advanced Research Projects Agency (DARPA) and TACOM to determine their level of interest.

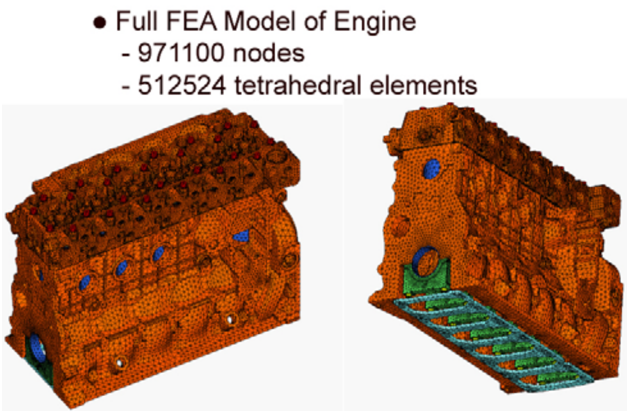

Figure 1. FEA model of the Cummins engine.

After the engine was modeled in Ti, two other lightweight materials, high-strength Al and high-strength Mg casting alloys, were modeled as replacements for cast iron in a diesel engine head and block at a normal maximum rating (305 hp). The alloys were A354-T6 AL and We-43-T6 MG. The stresses and fatigue safety factors in the block were found to be acceptable. The same was true for the head. However, the temperatures in the valve bridges were of concern based on the results of the Ti modeling. The results of the thermal FEA of the engine head are shown in Figure 2.

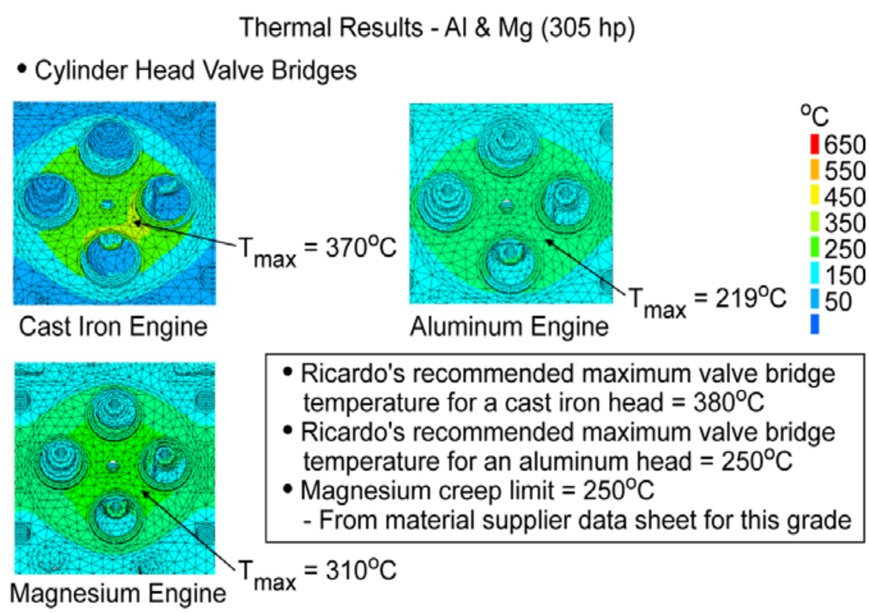

Figure 2. Thermal results comparing the valve bridge region in the head for production cast iron, Al, and Mg.

The FEA results show that the temperatures are low enough to be considered acceptable, keeping in mind that the analysis assumed that the engine was running at maximum power throughout its life, which does not mirror reality. The temperature of 310°C in the Mg head was somewhat high, but for this study it was not high enough to make the head unfeasible in this material.

The potential overall engine weight saving was 20% for Al and 33% for Mg. Most of the FEA work was done in FY 2004, but some details were completed in FY 2005. These involved calculating weight benefits and presenting the work to potential customers and manufacturers.

Since the commercial Cummins engine weighs about 1100 lb, 220 lb could saved if the head and block were made of Al and 363 lb could be saved if made from Mg. All of these data and analyses were presented to Cummins and Caterpillar as well as to TACOM in FY 2005.

SLC of Al for Turbocharger Compressor Wheels

SLC is a lower-cost approach to semi-solid forming (SSF) of Al castings. The advantage of the SSF process is that a nearly porosity-free casting can be made that results in high fatigue strengths. The process is attractive for making high-performance diesel engine turbocharger compressor wheels. Using the SLC approach solves two major problems inherent in traditional SSF processing. First, since the semi-solid charge is produced in the heating chamber of the die casting tooling, the cost to produce a part is nearly the same as for a traditional die casting. This contrasts with a 25% cost premium for parts made by traditional SSF. Second, SLC requires only about 5000 psi to force the slurry into the mold; traditional SSF requires 20–25,000 psi. Therefore, a plaster mold or some other destructible material could possibly be used to make the compressor wheels, which is a requirement. The severe curvature of the compressor wheel's vanes makes it impossible to extract a casting from hard tooling. Figure 3 is a schematic drawing of the SLC concept.

SLC cast test bars of A354 were made at THT Presses and then heat-treated to T-6. These bars were sent to Metcut Research for machining and testing. The data were then to be compared with semi-permanent mold castings made from the same alloy. Tensile test data are shown in Table 1. The table compares data from test bars cast by the SLC process to data from permanent mold test samples cast with the same alloy and heat treatment process.

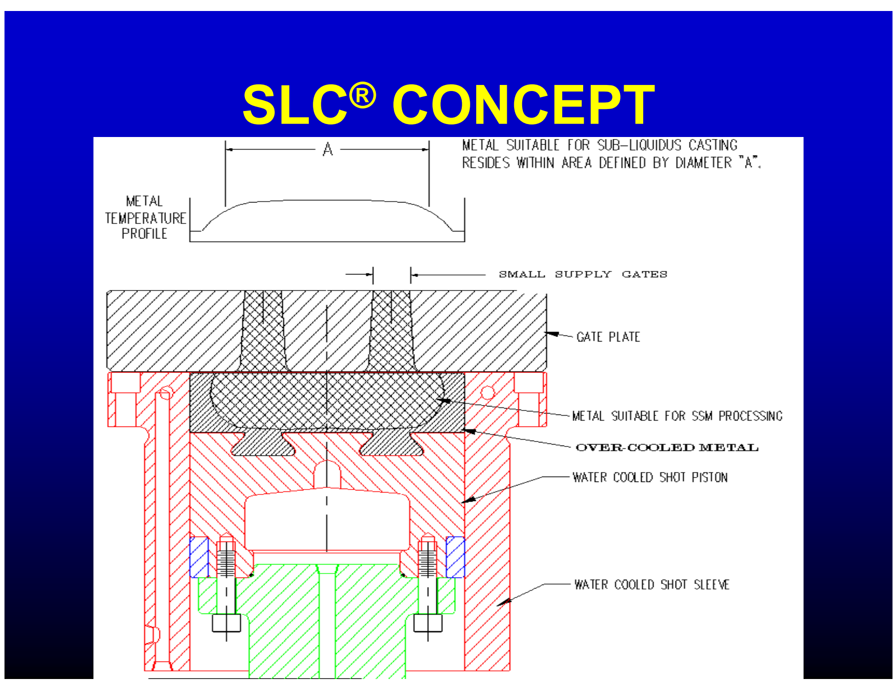

Figure 3. Schematic drawing of the SLC casting chamber.

Table 1. Comparison of permanent mold cast to SLC A354-T6

Test temp. (°C)	UTS (Ksi)	0.2% YS Ksi	Elongation (%)
Permanent mold (no chill)			
Room temp	38.5	35	0.57
150	31	30	0.37
200	29	29	0.33
260	21	20	1.1
Sub-liquidus			
Room temp.	46	40	1.8
150	42	35	3.9
200	36	34	1.7
250	26	24	3.8

UTS = ultimate tensile strength
YS = yield strength

The fatigue properties at room temperature of samples made by the SLC process were measured at Metcut Research using the rotating beam technique, and the data were compared with permanent mold data produced for Cummins in an earlier DOE-funded program. Cummins did the data analyses using its proprietary fatigue analysis software FATIGUE. The comparison is shown in Figure 4.

As can be seen from these two S/N curves, the SLC process provides a slightly higher fatigue life at cycles greater than 10^7, which is more pronounced at 5×10^7 cycles. Unfortunately, the SLC samples had higher than expected porosity, which would explain the high scatter in the data. Optical microscopy of the SLC cast bars conducted at ORNL (Figure 5) shows the porosity.

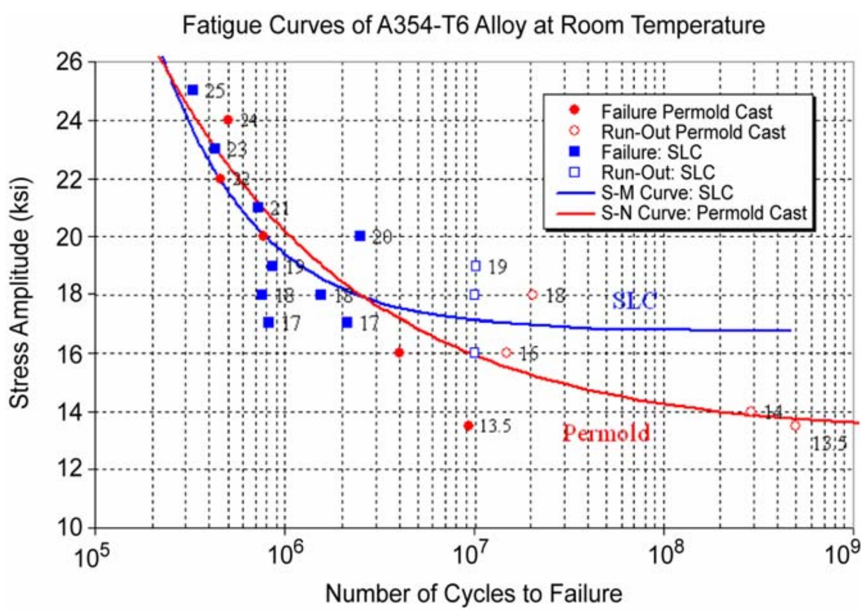

Figure 4. Comparison of rotating beam curves of permanent mold and SLC castings of A354-T6.

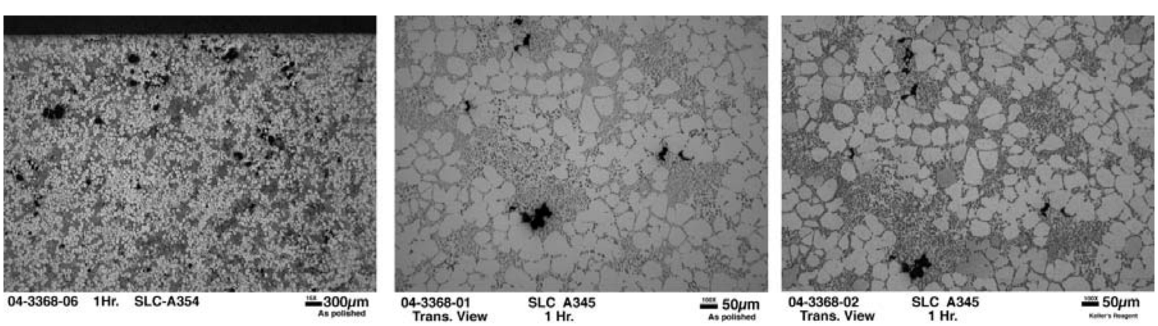

Figure 5. Micrographs of SLC samples showing the porosity from the casting process. The micrographs are from the infrared heat-treated sample.

Figure 6 shows the microstructure of the SLC cast bars. The micrograph on the left shows the conventional T-6 heat-treated microstructure, and the one on the right shows the infra-red heat-treated microstructure. In both cases, the microstructure is finer than for the permanent mold castings of the same alloy, but using infra-red provides an even finer structure and hence even higher mechanical properties. The fine microstructure explains why the cycle fatigue life of the SLC samples is higher than that of the permanent mold samples even though the SLC castings do not have optimum structure because of the high porosity.

THT Presses has promised to replace these samples with higher-quality cast bars so that a more definitive evaluation can be made.

Conclusions

- FEA modeling has confirmed that it is feasible to substitute Al and Mg for cast iron in the head and block of a heavy-duty diesel engine. This substitution can result in an overall engine weight saving of 20% for Al and 33% for Mg. Although this work and the previous work on Ti were presented numerous times to TACOM, DARPA, Cummins, and Caterpillar, none of these organizations has yet committed funding to continue the program.
- The SLC process was given a preliminary evaluation. Mechanical property data from A354-T6 samples were generated and compared with data of the same alloy that was permanent mold cast. The ultimate tensile strength at room temperature for the SLC cast bars was about 19% higher than for the permanent mold cast bars, and the yield strength was about 14% higher. The extrapolated fatigue life of the SLC process produced a 17% improvement over that of the permanent mold cast samples at 5×10^7 cycles.

If the SLC samples contained the very low porosity that the process is capable of, even higher fatigue properties should be achievable.

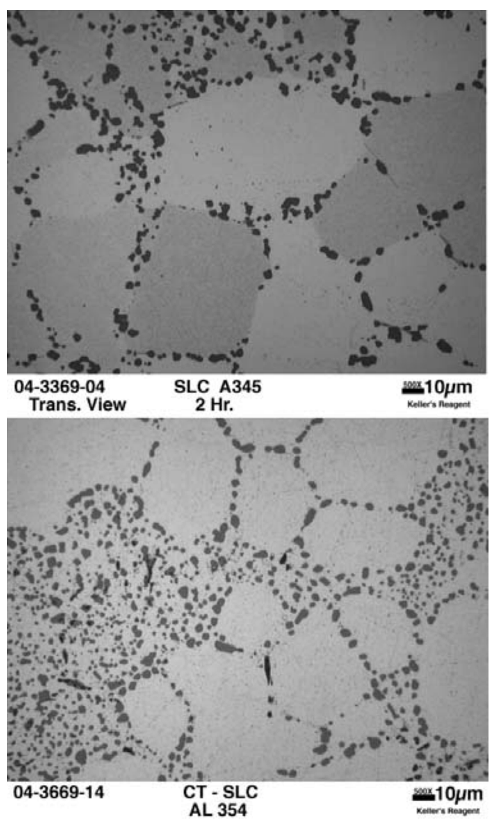

Figure 6. Microstructures of SLC samples that have undergone either conventional T-6 heat treatment or infra-red heat treatment.

Presentations

Puja B. Kadolkar, Craig A. Blue, Qingyou Han, and Paul C. Becker, "Rapid Infrared Heat Treatment of Al Cast Structures," presented to the Materials Science and Technology 2005 Conference and Exhibition, September 25–28, 2005.

P. C. Becker, presentation on Ti, Al, and Mg in diesel engines to Caterpillar, April 27, 2005.

P. C. Becker, presentations on Ti, Al, and Mg in diesel engines to Cummins, April 25, 2005.

P. C. Becker, presentation on Ti, Al, and Mg in diesel engines to TACOM, April 15, 2005.